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# Op Amp Design

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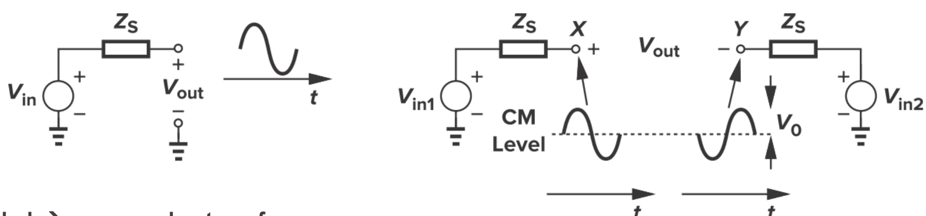
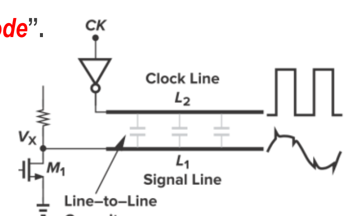
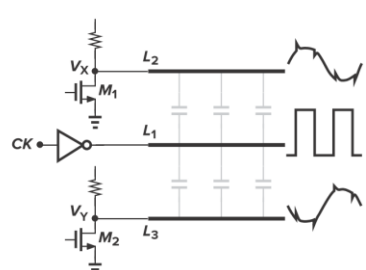
## Single Ended Vs Differential

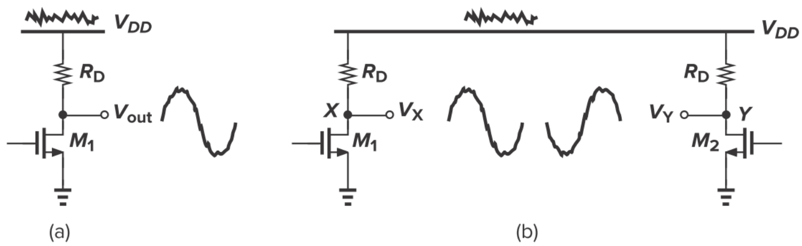



- Single ended → measured wrt a reference.
- Differential→ measured between two nodes that have equal and opposite signal excursion around a fixed potential.
- Fixed potential is called "***Common Mode***".
- The two nodes should exhibit equal impedances to that potential.
- Why differential??



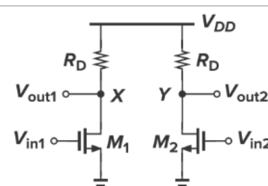
## Why Differential?



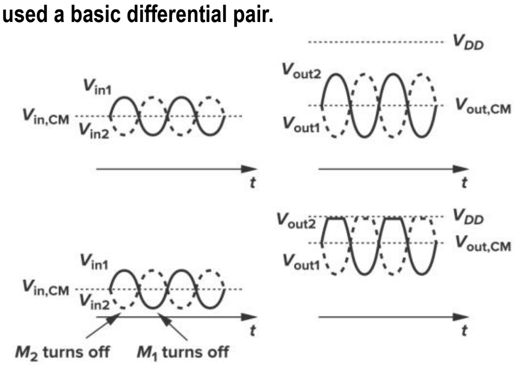

- Supply noise also shows as common mode jumps which get finally cancelled.
- Higher signal swing→ circuit (a) has swing of $V_{DD}$-($V_{GS}$-$V_{TH}$) while that of (b) has twice as much.
- Higher linearity.



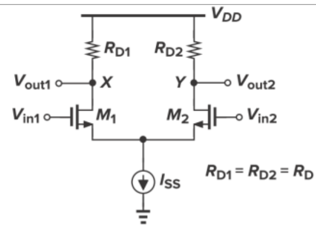
## Basic Differential Pair-Psuedo-Differential




- Two single ended pair is getting differential inputs can be used a basic differential pair.
- However, very sensitive to "Common Mode".
- This topology is also called "*pseudo-differential pair*".



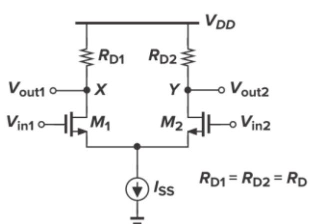
# Basic Differential Pair-Fully Differential Pair



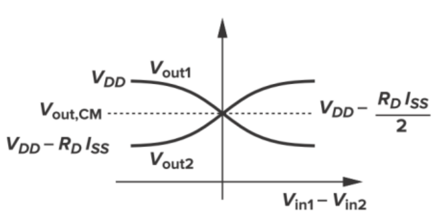

- Not sensitive to “Common Mode”.
- This topology is also called “*fully-differential pair*”.
- Large signal analysis:
  - Qualitative
  - Quantitative

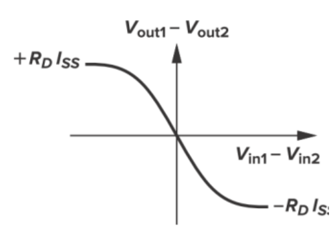


# Qualitative Analysis Differential

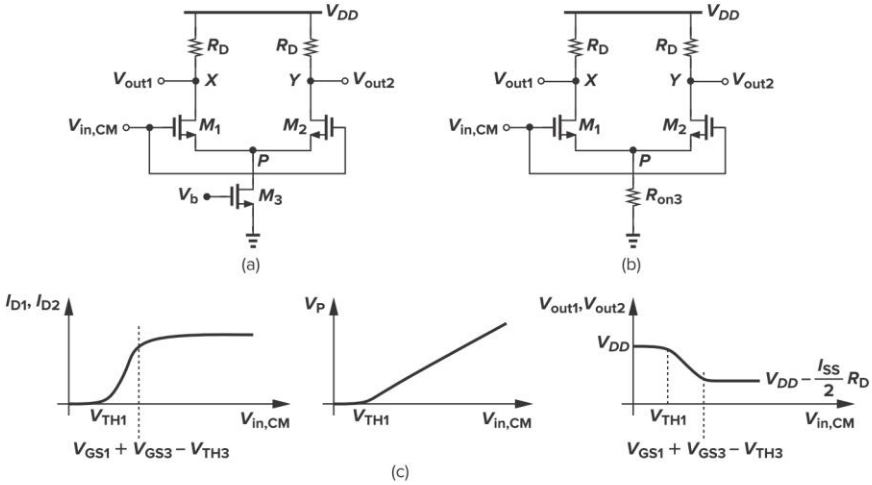



- Outputs are well defined
- Maximum slope when $V_{in1}$=$V_{in2}$ and get nonlinear when the signal swing gets larger.



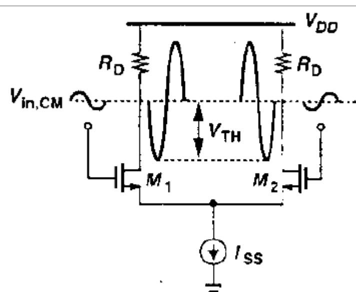
# Qualitative Analysis Common Mode




$$V_{GS1} + (V_{GS3} - V_{TH3}) \leq V_{in,CM} \leq \min\left[V_{DD} - R_D\frac{I_{SS}}{2} + V_{TH},\ V_{DD}\right]$$

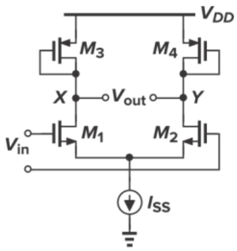


# Qualitative Analysis Maximum Output Swing

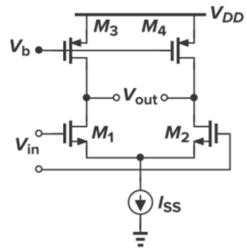



- Higher the input common mode lower is the output swing.
- Desirable to have low common mode.
- Preceding stage might have a problem giving such a low common mode.

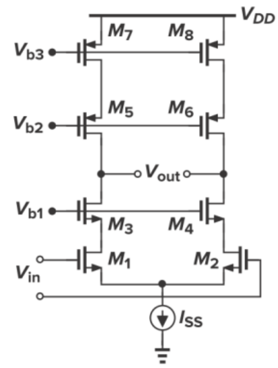
## Diff Pair with MOS Load




Diode Connected Load




Current Source Load



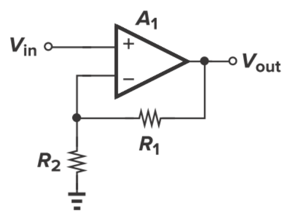

Cascode Differential Pair



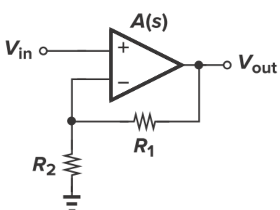
## Introduction to Operational Amplifier (Op amp)

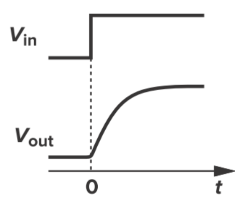
- Operational amplifier is a “high gain differential amplifier”.
- Performance parameters of an op amp:
  - Open loop gain → called DC gain
  - Small signal bandwidth → defined by unity gain BW.
  - Large signal bandwidth → typically defined by slew rate
  - Output swing → decides your noise performance
  - Linearity
  - Noise and offset → decides your SNR.
  - Supply rejection → robustness of the circuit to supply noise.

# Example-Typical Application




Single-pole Amplifier has 3 dB BW of 1MHz
What is UGBW of the amplifier? If open-loop gain is 60 dB?




**What should be $A_1$ for a gain error < 1%?**

$$\frac{V_{out}}{V_{in}} = \frac{A_1}{1 + \frac{R_2}{R_1 + R_2} A_1}$$

$$= \frac{R_1 + R_2}{R_2} \frac{A_1}{\frac{R_1 + R_2}{R_2} + A_1}$$

**$V_{out}$ should be close to ideal $V_{out}$ by 1%.**

**➔ $A_1$ > 1000**

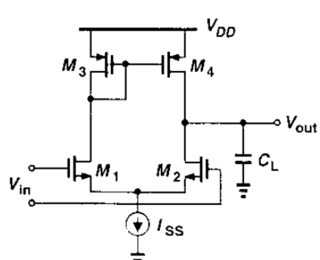
**What should be UGBW of op amp for output to settle to 1% accuracy in 5 ns?**

$$\frac{V_{out}}{V_{in}}(s) = \frac{A_0}{1 + \frac{R_2}{R_1 + R_2} A_0 + \frac{s}{\omega_0}}$$

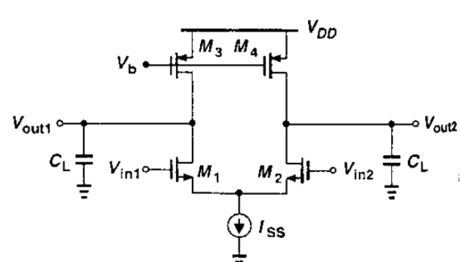
$$\tau = \frac{1}{\left(1 + \frac{R_2}{R_1 + R_2} A_0\right) \omega_0} \quad ➔ \quad 1 - \exp\frac{-t_{1\%}}{\tau} = 0.99$$



# Single Stage Op amp-1



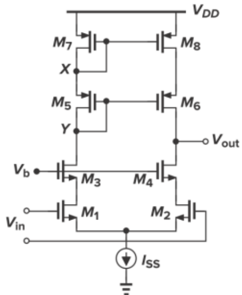

**Single Ended**



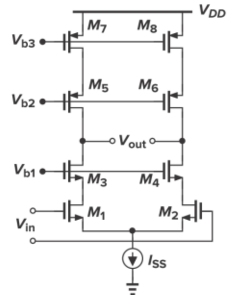

**Fully Differential**

- ❑ **Gain = $g_{mn}(r_{on}||r_{op})$**
- ❑ **Difficult to get gain > 20 in deep sub-micron CMOS.**
- ❑ **Speed depends on CL.**
- ❑ **Single ended version exhibits a mirror pole ➔ slower than fully differential.**

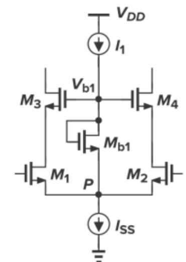
## Single Stage Op ampTelescopic Op amp




Single Ended




Fully Differential



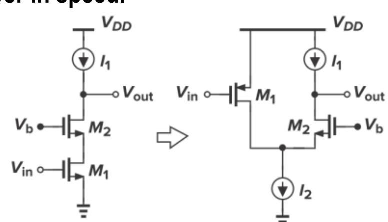

Generation of Cascode Gate Voltage

- ❑ Gain $\approx g_{mn}((g_{mn}r_{on}{}^{2})||(g_{mp}r_{op}{}^{2}))$
- ❑ Can get gain up to 1000 or more.
- ❑ Speed depends on CL.
- ❑ Single ended version exhibits a mirror pole.
- ❑ Output swing = $V_{DD}$-$V_{DSAT2}$-$V_{DSAT4}$-$V_{DSAT6}$-$V_{DSAT8}$-$V_{CSS}$

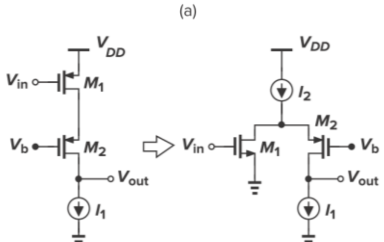


## Folded Cascode-Principle and Op amp

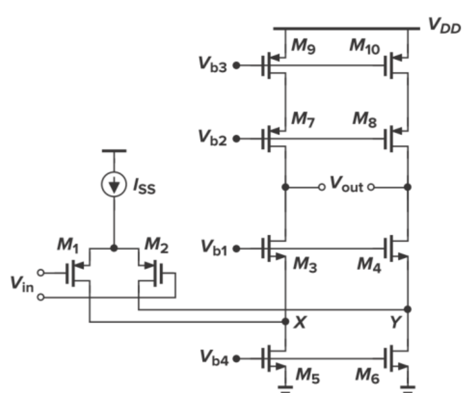
- Enables shorting of the output to the input.
- Slower in speed.



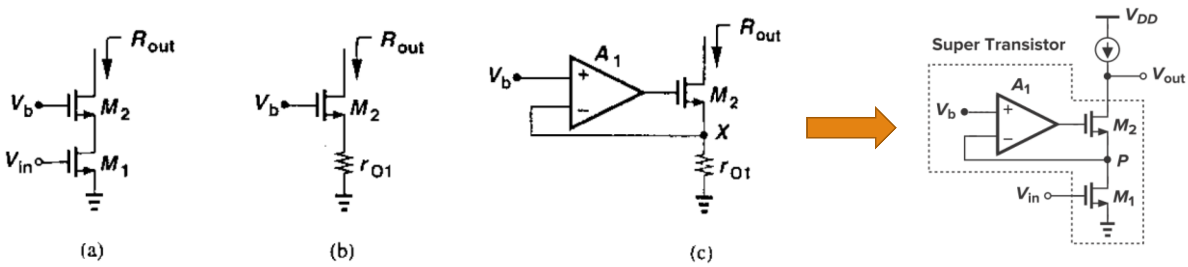

(a)




(b)



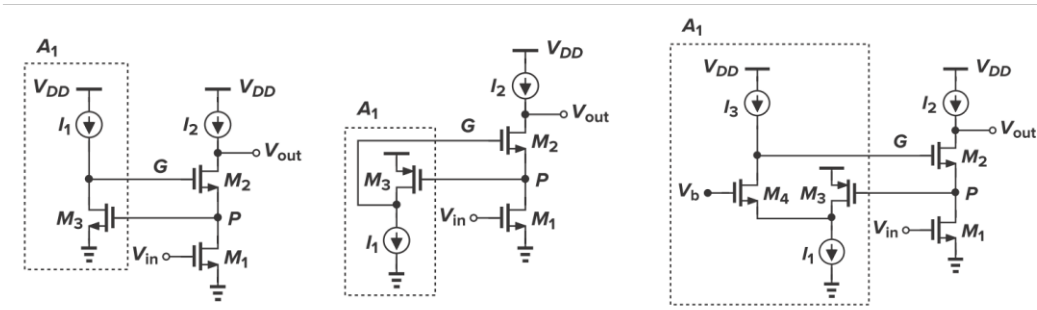
## Gain Boosting




- ❑ Fig (a) ➔ $R_{OUT}=g_{m2}r_{o2}r_{o1}$
- ❑ Fig (c) ➔ $R_{OUT}=A_1 g_{m2}r_{o2}r_{o1}$



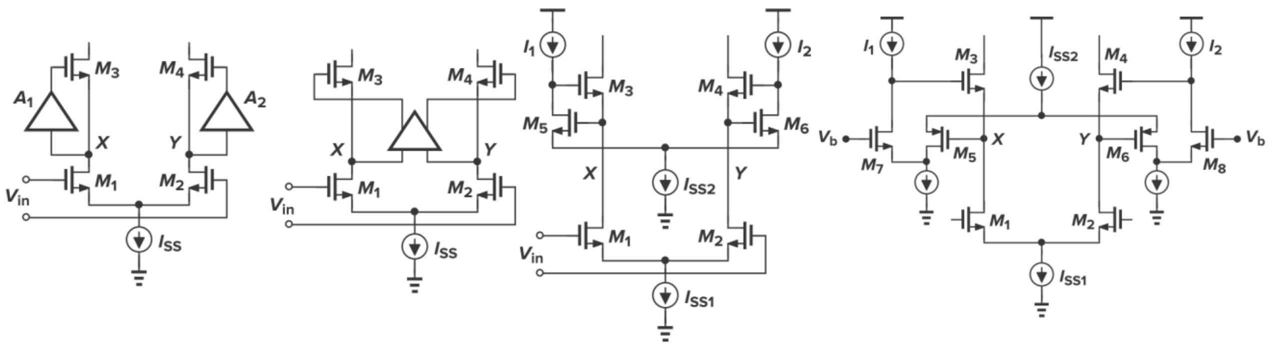
## Gain Boosting Amplifier




NMOS CS-stage PMOS CS-stage Folded Cascode stage

- NMOS CS stage would require that $V_{DS}$ of $M_1$ be large ➔ reduces headroom
- PMOS CS stage would require that Gate of $M_3$ may be driven to triode as $V_{GP} = V_{TH} + Vds_{at}$.
- The folded cascade mitigates the above two problems.

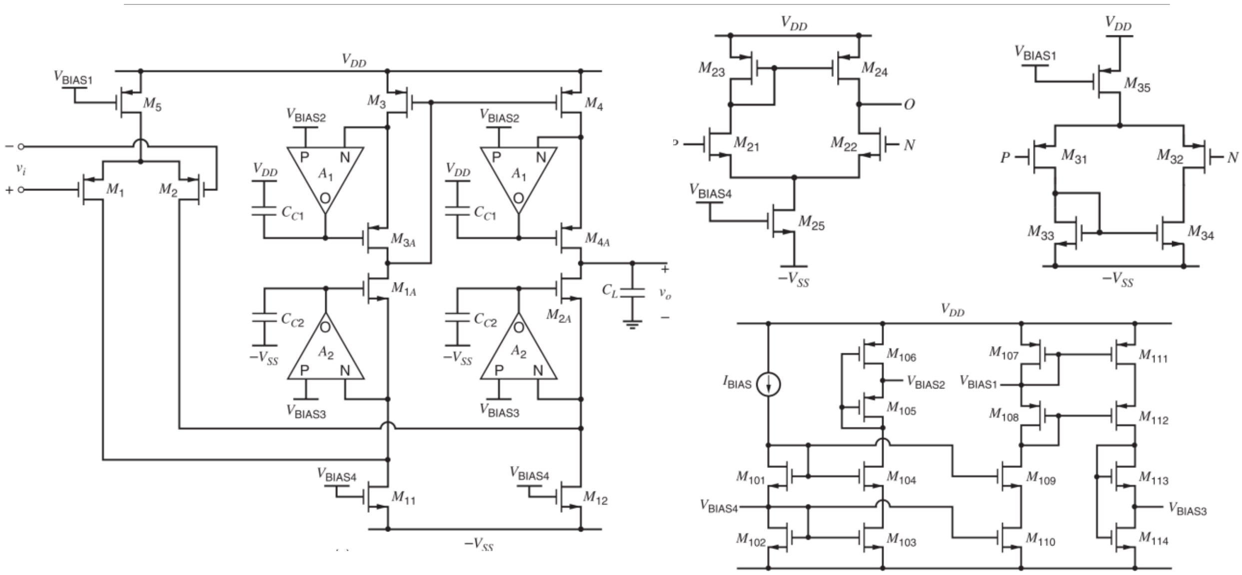
# Gain Boosting Amplifiers in Differential Pair




- Same trade-off as earlier exists and therefore the folded cascade as shown in the rightmost figure will be prererred.



# Gain Boosting ➔ Generic Topology With Biasing



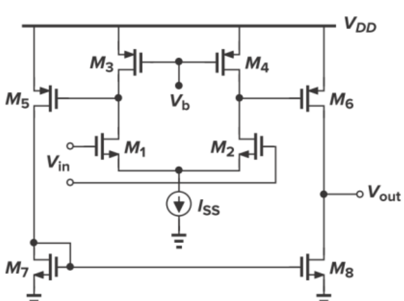
## Comparison of Performance of Various Op Amps

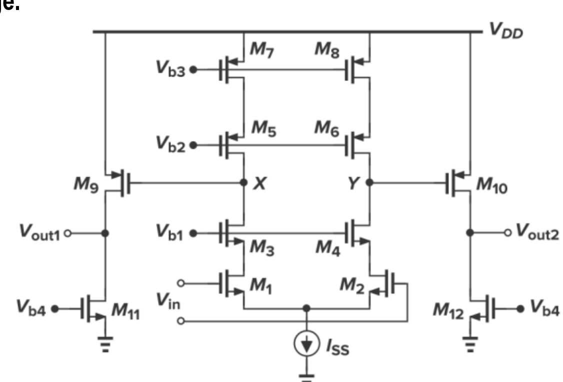
| | Gain | Output Swing | Speed | Power Dissipation | Noise |
|---|---|---|---|---|---|
| Telescopic | Medium | Medium | Highest | Low | Low |
| Folded–Cascode | Medium | Medium | High | Medium | Medium |
| Two–Stage | High | Highest | Low | Medium | Low |
| Gain–Boosted | High | Medium | Medium | High | Medium |



## Two-Stage Op Amps-1

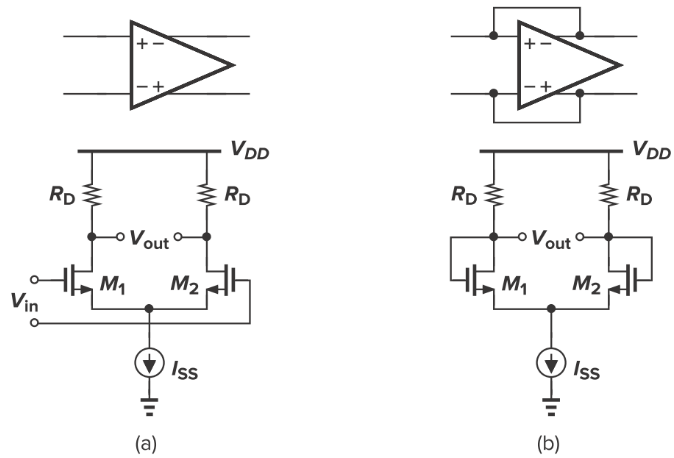
- Provides
  - High gain
  - High swing
- Typically 1st stage incorporates all the topologies studied earlier
- Second stage is just a common source stage.



# Common Mode Feedback (CMFB)

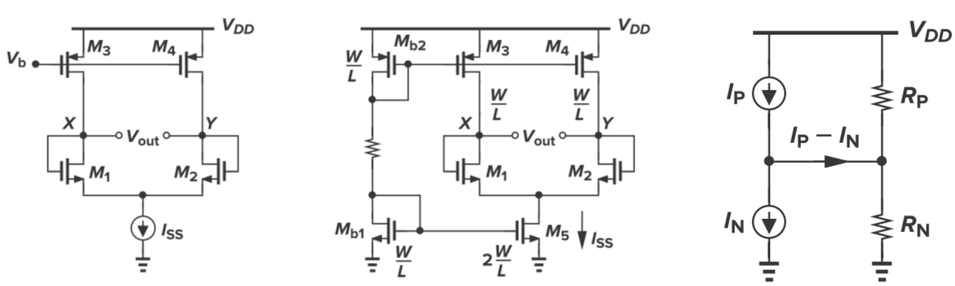
- Need for CMFB:
  - Define the output CM properly.




Output CM is
$V_{O\ CM} = VDD - RDIS_S/2$
and is well defined.

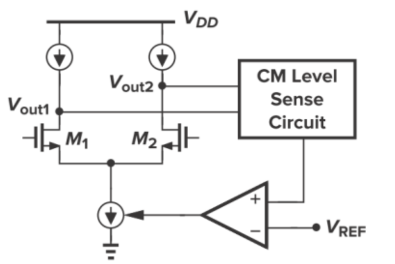


# Common Mode Feedback (CMFB)

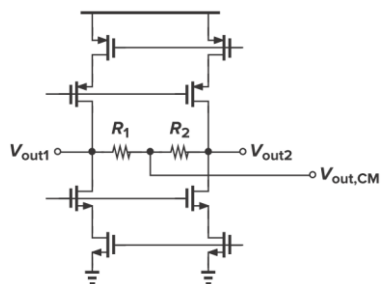



- Output CM is not well defined.
- Trying to match NMOS current source with PMOS current source.
- The output CM is poorly defined as the output CM depends on the device properties.
- Any mismatch in the PMOS and NMOS currents would lead to either the PMOS or NMOS trying to correct itself to satisfy KCL, thereby getting into triode mode.

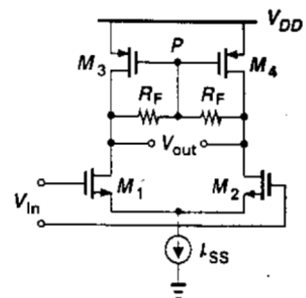
## CMFB




- Dynamically sense the CM and control either the PMOS or NMOS current source so that they match.

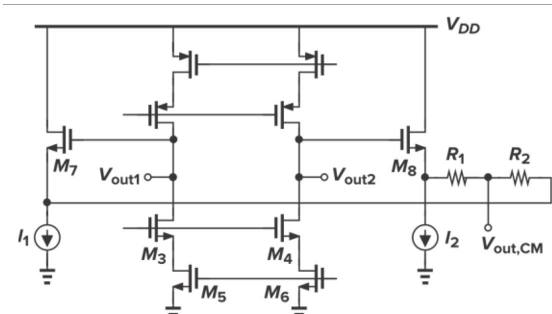



- Reduces the gain.
- If $R_1$ and $R_2$ are very high then it slows down the circuit.

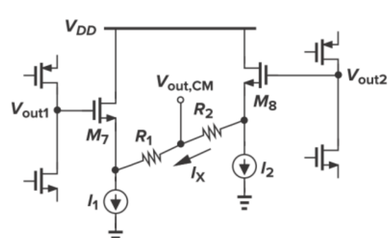




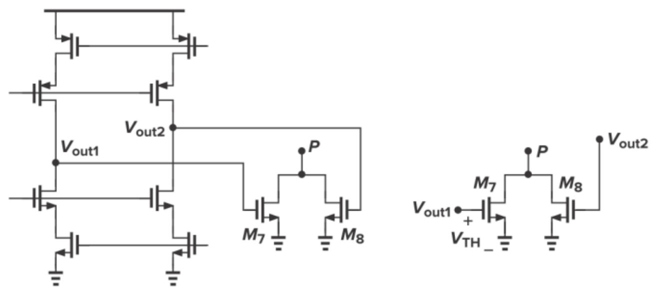

## Source Follower CM Sensing




- Doesn't reduce the gain but is very slow.
- Suffers from current starvation during output swing
  - Assume $V_{out2}$ is much higher than $V_{out1}$
  - Note: $I_X + IM_7 = I_1$ ➔ If $R_1$ and $R_2$ are large then $I_X$ is small otherwise $I_{M7}$ reduces to 0 ➔ output CM is not exactly sensed ☹.



## CM Sensing using Triode Connected Transistor




Resistance between node P and ground is dependent on the CM as shown below:

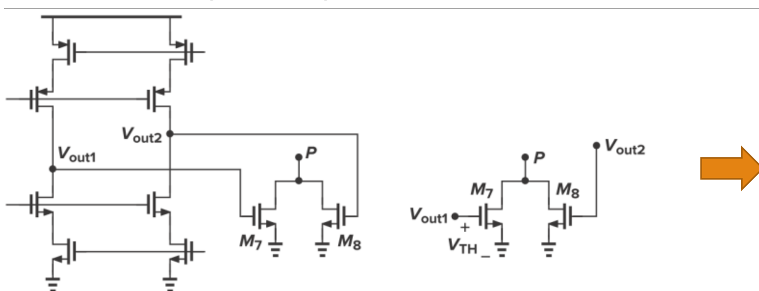
$$\mathrm{R_{tot}} = \mathrm{R_{on7}}||\mathrm{R_{on8}}$$

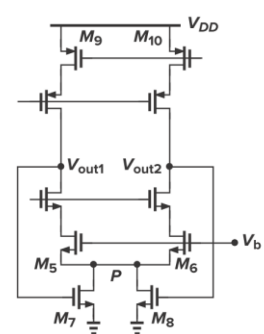
$$= \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{out1}-V_{TH})}\Big|\Big|\frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{out2}-V_{TH})}$$

$$= \frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{out2}+V_{out1}-2V_{TH})}$$



## CM Sensing using Triode Connected Transistor

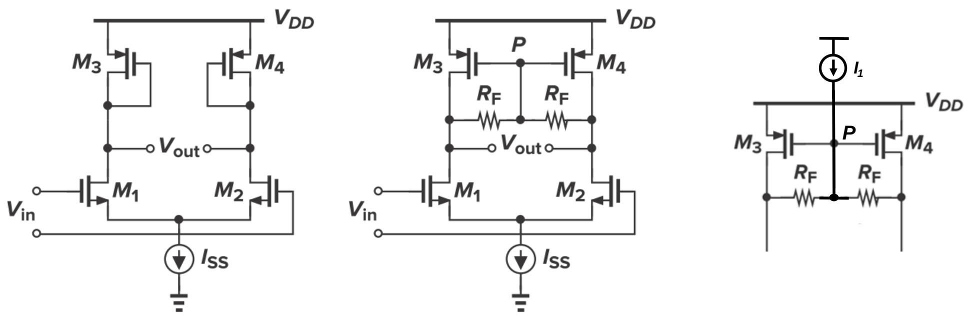



- Let, $I_{D9} = ID_{10} = ID$ , then $V_b - V_{GS5} = 2I_D(R_{on7}||R_{on8})$ resulting in $\frac{1}{\mu_n C_{ox}\frac{W}{L}(V_{out2}+V_{out1}-2V_{TH})} = \frac{V_b - V_{GS5}}{2I_D}$

  thus, $$V_{out1} + V_{out2} = \frac{2I_D}{\mu_n C_{ox}\left(\frac{W}{L}\right)_{7,8}}\frac{1}{V_b - V_{GS5}} + 2V_{TH}$$
- Drawback-1➔ The output CM is a function of the device parameter ➔ not a good thing.
- Drawback-2 ➔ The voltage drop across $R_{on7}||R_{on8}$ limit the headroom.
- Drawback-3 ➔ If M7 and M8 are made large to reduce $R_{on7}||R_{on8}$ then the output capacitance increases compromising speed.

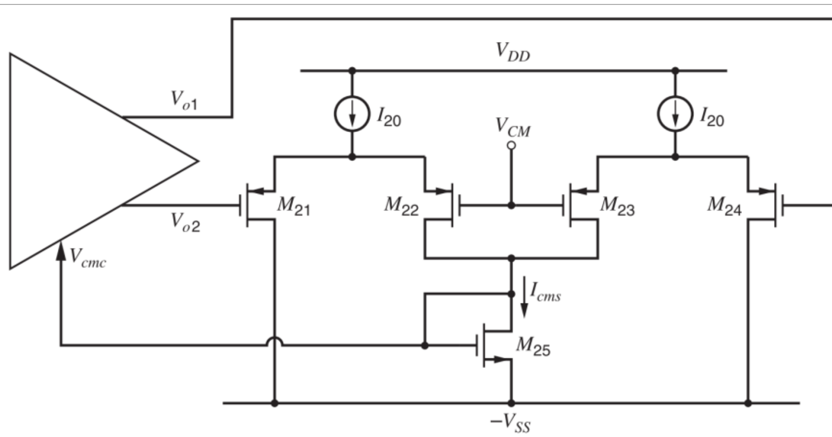
## Resistive CMFB with Large Swing




- Resistive feedback causes $V_{DS3} = V_{DS4} = V_{GS}$ ➔ compromising swing.
- By pumping current into $R_F$ the voltage at node P goes up reducing $V_{GS4,5}$ ➔ reducing $V_{dsat4,5}$ ➔ better swing.

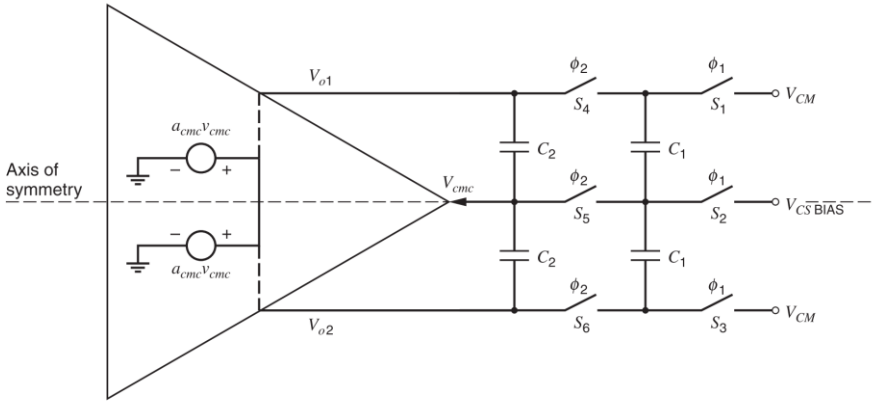


## Differential Pair CMFB




- Doesn't reduce the gain
- Is fast
- But cannot sense large swings at the output ➔ typically used in CMFB of the 1st stage of op amp

# Switch Capacitor CMFB




- **Doesn't reduce the gain**
- **Load the op amp and slows it down**
- **Susceptible to capacitive attenuation**
- **Can sense large swings and therefore can be used for CMFB of the 2nd stage of a 2-stage op amp**
- **Requires non-overlapping clocks**